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Excavation tool concepts for TBMs – Understanding the material-dependent response to abrasive wear

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ABSTRACT

Wear of cutting tools for tunneling applications can lead to decreased advance rates and unscheduled downtimes that are associated with increased tunneling times and project costs. During the planning phase, wear of tools and their associated lifetime and replacement times are estimated on the basis of the ground that is to be excavated. However, from the viewpoint of materials technology, this procedure is insufficient because it is essential to take account of the interactions between tool material, ground, and the acting wear mechanisms on the microscopic scale, such as abrasion, fatigue, or forced fracture. The respective tool materials feature different tribomechanical properties and thus different wear mechanisms and rates that depend on the ground to be mined. Low wear rates can only be achieved using an optimized tool material concept that is adapted to the acting ground and the associated tribological system. This requires a comprehensive understanding of the wear behavior of the respective materials. This article focuses on the different, commonly used tool concepts and their microstructure. Interactions of the microstructure of these materials with the abrasive particles and the associated microwear mechanisms are analyzed. The results provide a deeper understanding of the wear process of excavation tools depending on the respective tool and the material concept. The discussed correlations are illustrated by results from the RUB Tunneling Device and nanoscratch tests, which are used to map the tribological TBM tool system on the macroscopic and microscopic scales.

1. Introduction

Underground and surface mining, tunneling, and rock drilling are procedures that are commonly used all over the world to create infrastructure and to exploit resources, for example. Even if the procedures and pursued objectives are different, the degradation process of the ground is similar for the respective techniques. Plinninger (2007) showed that rock or soil quarrying places high demands on excavation tools due to severe wear. In this work, we focus on mechanized tunneling, which is vital to ensure necessary infrastructure development in megacities such as Tokyo (Bay Tunnel), Istanbul (Eurasia Tunnel), and Mexico City (Emisor Oriente Tunnel). In contrast to conventional methods such as drilling and blasting or excavation using dredgers, tunneling with TBMs allows simultaneous excavation and removal of the ground in conjunction with lining the resulting tunnel with tubbing segments or shotcrete. This makes tunneling more efficient, allowing faster development of the tunnel in both hard rock and soil as concluded by Maidl et al. (2013). Budgeting a tunneling project requires precise planning and coordination with respect to selection of the tunneling technique (e.g. EPB or slurry-shield) as well as the relevant ground, associated penetration rates, and tool wear. In particular, wear of TBM tools has a significant impact on the tunneling process. Because of continuous wear, tools become dulled or lose their functionality, thus reducing penetration rates and therefore the tunneling efficiency (Maidl et al., 2013). As a result, additional tool changes are necessary, leading to higher overall costs due to downtimes and maintenance work.

In this context, high motivation exists to understand and to control the wear processes of tools during ground removal. Therefore, tool materials and their wear mechanisms have to be analyzed in detail in terms of the respectively present tribological system. The tribological system defines the wear process, which is dependent on the load, ground, tool material, and surrounding/intermediate medium. Changing one system component influences the overall wear characteristics, illustrating that wear is not a material property. However, wear can be reduced by selecting an appropriate material/ground combination with respect to the encountered loads. Beste et al. (2001) showed for example that percussion drilling leads to a load spectrum that promotes fatigue and surface breakdown of the tools. Therefore, the tool material should have a sufficient fracture toughness and hardness

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to avoid fast crack propagation and indentation of the abrasives into the tool material. In contrast, a disc cutter rolls over the ground with a high contact pressure, which leads to rock chipping (Rad, 1975). Schneider et al. (2010) illustrated that the tool must have a high toughness and compressive strength to withstand the high stress, otherwise it would fracture or burst. Other examples mentioned by Thuro (2002) are ablative/shearing tools (e.g. bucket teeth, chisel tools, etc.) that are worn due to abrasive removal of the surface. Thus, the hardness and abrasive wear resistance of the tool material and the interaction between the microstructural constituents of the tool material and the abrasive particles are of great importance.

This article focuses on the degradation process and the resulting wear of TBM tools depending on the respective material. Different tool concepts will be discussed with regard to the ground to be excavated and the associated signs of wear. Tool materials are presented to create an understanding of the variable material-dependent wear behavior with regard to their microstructure. Finally, methods to determine the wear of excavation tools are illustrated and discussed. The author notes that the focus is not to analyze recent investigations on wear issues in TBM tunneling. This would go beyond the scope of this publication. Therefore, the author refers to Rostami et al. (2014) and Kuepferle et al. (2015, 2016b), which focus especially on this topic.

2. Tool concepts

Several tool concepts for TBMs have been developed that depend on the ground to be excavated (Fig. 1). These tool concepts (cutting discs, chisel, and reamer) differ with respect to their excavation mechanism for the type of ground (for example hard rock or soil).

Disc cutters are generally used for hard rock. They consist of a bearing casing and a cutter ring, as shown in Fig. 2a. During excavation, the cutter ring rolls over the tunnel face with high contact pressure, resulting in the generation of Hertzian pressures in the ground under the working face (Maidl et al., 2013). Due to the fact that the highest shear stresses caused by these Hertzian loads are located beneath the surface to be excavated, crack initiation and propagation occurs at geological inhomogeneities (Rad, 1975). The crack propagates through the ground, thus leading to the formation of crack networks that are accompanied by brittle break-out of material. In the case of soft rock or soil, the cutter head can also be equipped with cutter discs if boulders or supporting walls have to be pierced. Depending on the geological situation, the cutter ring is simultaneously worn by this rolling and sliding process, which leads to different signs of wear (Fig. 3) summarized by Rad (1975) and Thuro (2011). In addition, boulders and supporting walls promote impact loads, which can result in the formation of cracks within the cutter disc material or to a brittle material failure.

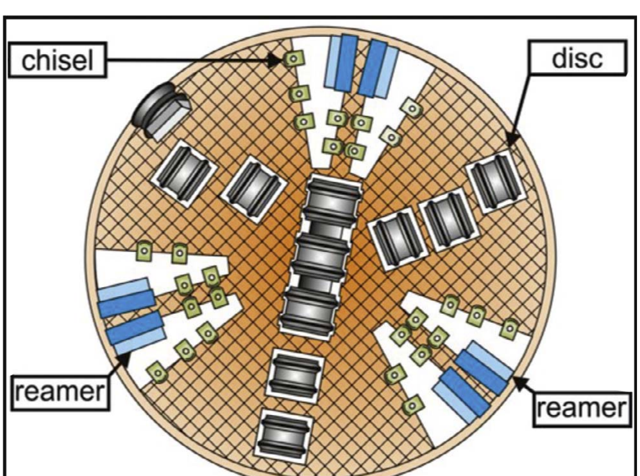

Fig. 1. Schematic cutter head of a TBM equipped with different tool concepts. Reamer, chisel (and ripper) tools are commonly used in soil. Disc cutters are mainly used for hard rock.

To withstand the high mechanical stresses while operating in hard rock, Frenzel et al. (2008) concluded that the cutting disc material should have a high material strength in conjunction with a high fracture toughness. On the one hand, a high material strength enables transmission of the forces required for quarrying the rock. On the other hand, a high fracture toughness is important to counteract brittle material failure due to spontaneous failure or to material fatigue caused by impact or cycling loads. In addition, Czichos et al. (1995) showed that 2-body (scratching of the tool material) and 3-body abrasion (indenting of the tool material) can be present, leading to continuous wear of the material surfaces. Abrasive particles indenting into the softer material cause material removal if moved relative to the material surface. In addition, cycling indentation of abrasive particles into the tool material can lead to disruption and break out of microstructural constituents (fracture of hard phases) (Czichos et al., 1995). Material removal can be countered by increasing the hardness, thus counteracting deep indentation by abrasive particles into the tool material (Berns and Theisen, 2008). In an optimized tool material, the hardness is as high as the hardness of the abrasive particle. However, a high material hardness is mostly associated with a decrease in fracture toughness, thus promoting fatigue wear and catastrophic failure, which is accompanied by a complete loss of functionality. Based on the aforementioned contrary requirements with regard to the material strength, hardness, and fracture toughness, hot-work tool steels (X40CrMoV5-1, X50CrMoV5-1) in the quenched and tempered condition are commonly used for cutting discs. As shown by Berns and Theisen (2008), the microstructure of these steels consists of a tempered metal matrix (high strength and toughness) containing eutectic and secondary carbides that are finely distributed in the metal matrix. An overview or classification of important mechanical properties is given in Table 1.

If disc cutters are used in soil, the cutter rings often penetrate deep into the soft ground. This leads to wear of the disc flanks (Fig. 3b), which is influenced by the penetration depth, the rotational speed of the cutter disc, and the ground to be excavated. In this case Rad (1975) concluded that 2-body abrasion (scratching of the material surface) becomes more pronounced. In addition, when the soil has a low density and/or shear strength, the torque required to rotate the disc cutter is not reached. The disc cutter is not rotating during excavation and wear of the cutter ring is localized on one side (Fig. 3c). Frenzel and Babendererde (2011) mentioned that the same behavior may occur if the bearing is clamped due to adhesive acting suspensions or mechanical failure. In the worst case, the cutter ring is worn to such an extent that the bearing casing is damaged as well and losses its functionality.

The other most commonly used group of excavation tools comprises chisel, reamer, and ripper tools which are generally used for quarrying soil (Fig. 4). Chisel and ripper tools are used to remove the soil by scratching the tunnel face (chisel tools have only one advance direction due to their geometry, and ripper tools can be used in both rotational directions of the cutter head). Reamer tools are used to transfer the quarried ground behind the cutter head into the excavation chamber of the TBM.

The three tool concepts are similar in terms of the used materials. Due to the different requirements with respect to wear resistance, toughness, and material strength, compound tools are used for quarrying soil, as shown in Fig. 4. This concept is also used for alternative disc cutter concepts (cutter ring with cemented carbide studs), which are used for specific types of ground (Fig. 2b). The base or main body (substrate) consists of low-cost steel grades (low-alloyed steels, construction steel, quenched and tempered steel) that feature a high toughness and good workability. The task of the steel substrate is to transfer the force from the tunneling machine into the ground being excavated. The functionality of the base body is lost if a high impact load causes plastic deformation or catastrophic failure, which can be